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THE RESPONSE OF A CYLINDRICAL SHELL TO BULK CAVITATION LOADING

BY MARTIN H. MARCUS

RESEARCH AND TECHNOLOGY DEPARTMENT

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An analysis is developed for the response of a cylindrical shell to a bulk cavitation loading. Due to the fluid-structure interaction inherent in the problem, it is convenient to use the USA-STAGS code. This program couples the fluid and structural motions using the Doubly Asymptotic Approximation (DAA) and solves for the structural response with the finite element method. In the example treated it appears that the bulk cavitation loading may be as damaging to the shell as the direct shock of the explosives.

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FOREWORD

An analysis is developed for the response of a cylindrical shell to a bulk cavitation loading. Due to the fluid-structure interaction inherent in the problem, it is convenient to use the USA-STAGS code. This program couples the fluid and structural motions using the Doubly Asymptotic Approximation (DAA) and solves for the structural response with the finite element method. In the example treated it appears that the bulk cavitation loading may be as damaging to the shell as the direct shock of the explosive.

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CHAPTER 1

INTRODUCTION

The concern of this report is to analyze the response of structures to bulk cavitation loading, a problem of great interest to the Navy.[1,2] An analysis is given for a cylindrical shell loaded first by a direct explosion pressure wave, then loaded by the surface reflection effects, including bulk cavitation closure.

The explosion loading has three phases:

i) the direct pressure,

ii) the pressure cutoff by cavitation, and

iii) the reloading at cavitation closure.

The USA-STAGS[3] structural computer program analyzes pressure loadings in an infinite acoustic medium on shells modeled with finite elements. This program can handle the first phase of the loading. The second phase of the analysis concerns the absence of loading on a structure initially set in motion in a gaseous medium. With no fluid-structure interaction, program STAGS[4] can handle this phase. The third phase again requires USA-STAGS.

The above procedure is undertaken for a finite element model of a 5.08 cm (2 in) length by 12.7 cm (5 in) radius steel cylindrical shell with a thickness of 8.19 mm (0.323 in). The cylinder has a 54.9 m (180 ft) standoff from a 18,141 kg (40,000 lb) charge of HBX-1.

---

[1]Snay, H. G., and Kriebel, A. R., "Surface Reflection of Underwater Shock Waves," NOLTR 70-31, Mar 1970.

[2]Gordon, J., and Costanza, F., "An Analysis of Bulk Cavitation in Deep Water," DTNSRDC LTR #1770-58, Aug 1980.

[3]DeRuntz, J. A., and Brogan, F. A., "Underwater Shock Analysis of Non-Linear Structures, A Reference Manual for the USA-STAGS Code (Version 2)," LMSC-D633864, Contract No. DNA 001-78-C-0029, Jan 1979.

[4]Almroth, B. O., Brogan, F. A., and Stanley, G. M., "Structural Analysis of General Shells," Volume II, User Instructions for STAGS, Structural Mechanics Laboratory, Lockheed, Palo Alto Research Lab, Palo Alto, California, Mar 1978.

CHAPTER 2

BULK CAVITATION LOADING

2-1 Bulk Cavitation

The term "cavitation" refers to the vaporization of water caused by a pressure drop below the vapor pressure of water. The term "bulk cavitation" refers to cavitation caused by reflection of an underwater explosion shock wave at the water surface.

2-1-1 Cavitation Boundaries

Figure 1 shows the geometry of the problem. "R_1" denotes the length of the direct path from the explosive charge to the gage. "R_2" is the length of the path reflecting at the surface, the image path. "α" is the angle of descent of the image path, and "d" is the charge depth. According to Arons,[5] at the upper cavitation boundary the total pressure is zero. Using similitude relationships to describe the direct and reflected pressures and an exponential time decay law for the direct pressure, one obtains:

$$K\left(\frac{W^{1/3}}{R_1}\right)^a e^{-t/\theta} \quad -K\left(\frac{W_i^{1/3}}{R_2}\right)^a + P_a + \gamma(R_2 \cos \alpha - d) = 0 \qquad (1)$$

which is equation (7) from Gaspin and Price[6]. "K" and "a" are similitude constants while "θ" is the exponential decay constant. "P_a" and "γ" are the atmospheric pressure and the specific weight of water. The arrival time difference, t, is simply:

$$t = \frac{R_2 - R_1}{c} \qquad (2)$$

where "c" is the speed of sound in water. "W" and "W_i" are the charge weight and image charge weight, respectively. The image charge weight is an apparent weight representing the pressure due to surface reflection. The image charge weight varies only in the cavitated region and such that the pressure in the region is zero.

---

[5]Arons, A. B., Yennie, D. R., Cotter, T. P., "Long Range Shock Propagation in Underwater Explosion Phenomena II," Underwater Explosions Research, Volume I, The Shock Wave, 1950, pp. 1473-1583.

[6]Gaspin, J. B., and Price, R. S., "The Underpressure Field from Explosions in Water as Modified by Cavitation," NOLTR 72-103, May 1972.

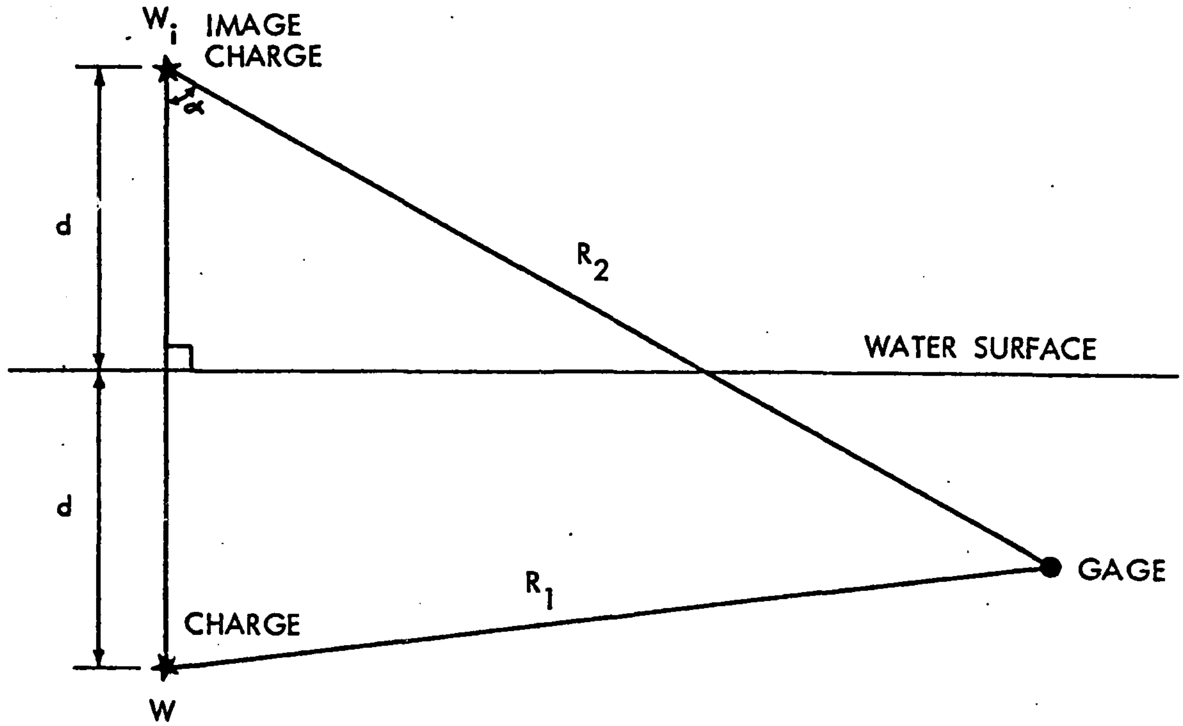

FIGURE 1. GEOMETRY FOR CAVITATION CALCULATIONS (FROM NOLTR 72–103)

The charge weight equals the image charge weight above the cavitated region; thus, Arons[7] finds the top of the cavitated region by setting:

$$W_i = W \quad . \tag{3}$$

Arons obtains the bottom of the cavitated region using the restriction:

$$\frac{dW_i}{dR_2} = 0 \tag{4}$$

since the image weight remains constant at locations under the cavitated region.

2-1-2 Cavitation Closure

Surface reflection causes the surface layer of water to spall upward. A one-dimensional view of this is seen in Figure 2. The upper region remains liquid, the middle region cavitates, and the lower region does not spall. The water from the cavitated region below the closure depth spalls and returns to its original location. When this layer of water, whose top is rising, meets the falling upper layer of water, cavitation closure occurs.

Snay and Kriebel[8] derive the closure depth by equating the times at which the upper and lower layers are at the same depth. Calling "D" the closure depth and defining the constant K as

$$K = \frac{c\ \theta}{2 \cos \alpha} , \tag{5}$$

the equation for closure depth is

$$1 + \frac{D}{K} + \frac{P_a}{\gamma K} = \exp\ (D/K) \tag{6}$$

from equation (5.9) of Snay and Kriebel[9].

This can be solved numerically, or one may use the approximate solution,

$$D = 4\ K^{.6212} \tag{7}$$

obtained from Figure 16 of Walker and Gordon[10].

---

[7]Arons, A. B., Yennie, D. R., Cotter, T. P., "Long Range Shock Propagation in Underwater Explosion Phenomena II."

[8]Snay, H. G., and Kriebel, A. R., "Surface Reflection of Underwater Shock Waves."

[9]Snay, H. G. and Kriebel, A. R., "Surface Reflection of Underwater Shock Waves."

[10]Walker, R. R., and Gordon, J. D. "A Study of Bulk Cavitation Caused by Underwater Explosions," DTMB Report 1896, Sept 1966, AD 643 548.

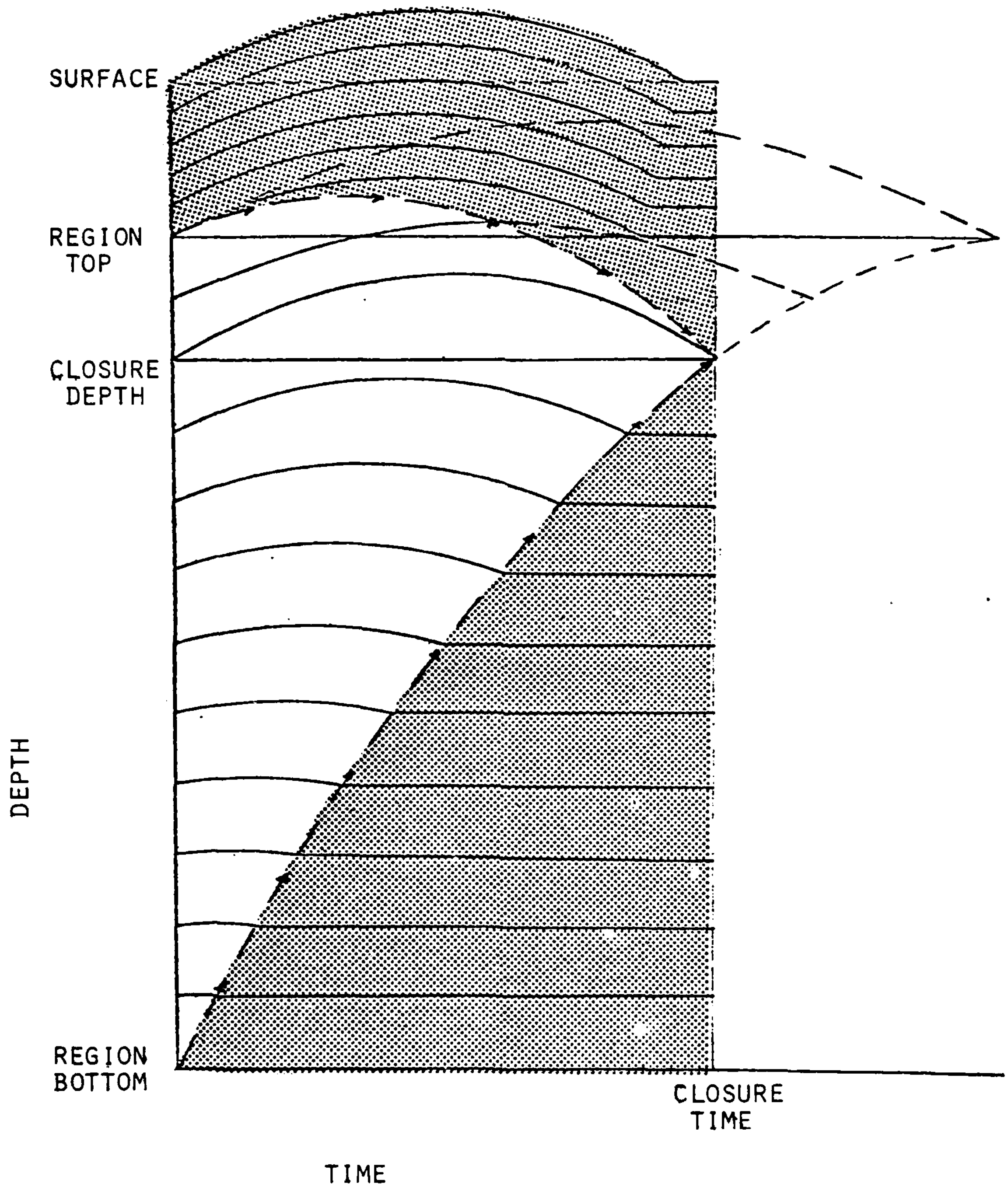

FIGURE 2. CAVITATION CLOSURE SEQUENCE

Snay and Kriebel[11] give the spall velocity as:

$$v = \frac{2P_F\theta}{\rho K} \exp(-D/K) \tag{8}$$

where "ρ" is the density of water. Assuming the spall velocity equals the closure velocity and assuming acoustic impedance, the closure pressure is

$$p_c = \frac{1}{2} \rho c v \tag{9}$$

where c is the sound speed in water.

Using the similitude relationship for the initial direct pr ure, P_F,

$$P_F = A\left(\frac{W^{1/3}}{R_1}\right)^a \tag{10}$$

the closure time, t_c, is

$$t_c = \frac{2P_F\theta}{\gamma(D+K)+P_a} \tag{11}$$

which is equation (5.10) in Snay and Kriebel[12].

2-2 Verification of Bulk Cavitation Theory

Of great interest is the pressure-time history of water undergoing bulk cavitation. Figure 3, from Gaspin[13], shows one such pressure-time history measured at 3.05 m (10 ft) depth and 51.8 m (170 ft) horizontal range from a 30.8 kg (68 lb) pentolite sphere at 21.3 m (70 ft) depth of burst.

Using the analysis in Section 2-1, one can obtain the cavitation boundary and closure curves. Figure 4 shows these curves from the explosion described above. Noting the distance of the gage to the explosive charge and its image, and the location of the closure point whose pressure first reaches the gage, we can calculate the closure pressure. The theoretical closure is characterized by only one point on the closure curve; thus, its pressure is a step input ending when the surface reflection of the closure reaches the gage.

---

[11] Snay, H. G., and Kriebel, A. R., "Surface Reflection of Underwater Shock Waves."

[12] Snay, H. G., and Kriebel, A. R., "Surface Reflection of Underwater Shock Waves."

[13] Gaspin, J. B., "Experimental Investigations of the Effects of Underwater Explosions on Swimbladder Fish, I: 1973 Chesapeake Bay Tests."

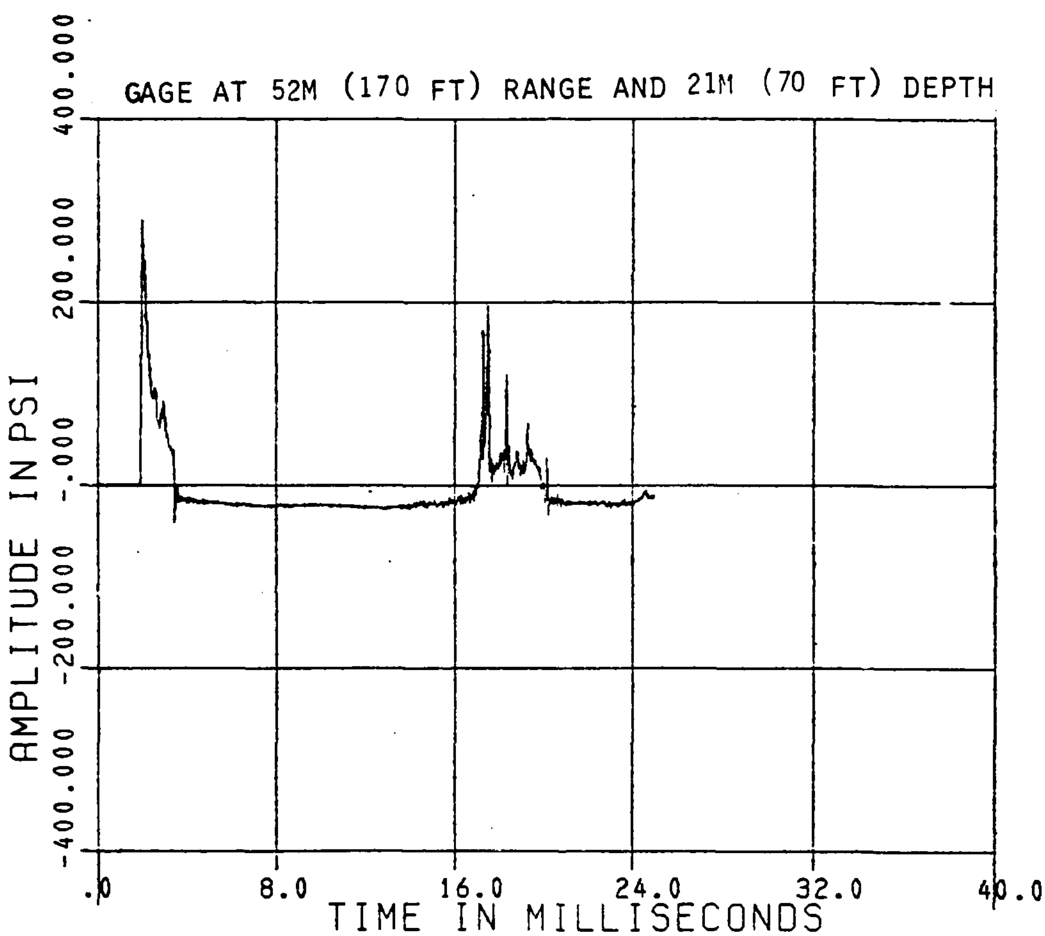

FIGURE 3. EXPERIMENTAL PRESSURE–TIME HISTORY FOR 30.8 KG (68 LB) CHARGE OF PENTOLITE

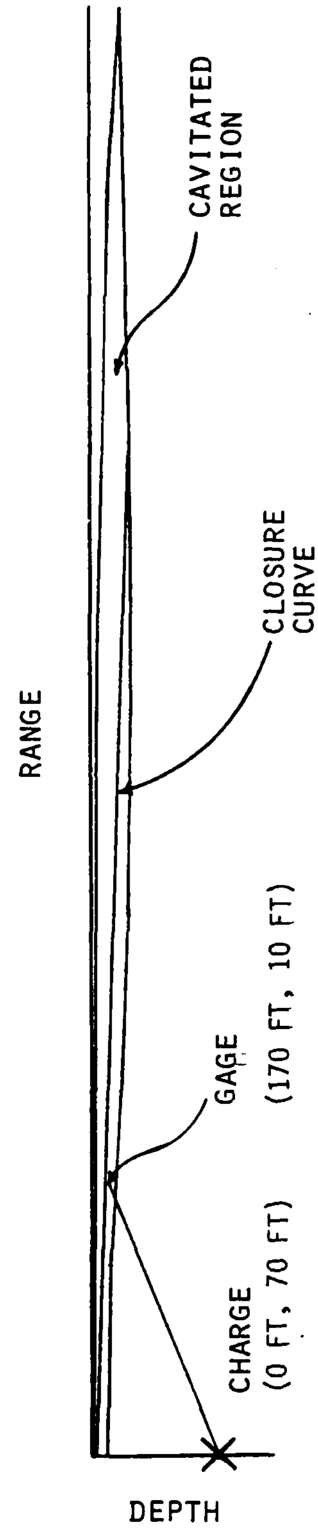

FIGURE 4. BULK CAVITATION FOR 30.8 KG (68 LB) CHARGE OF PENTOLITE

Figure 5 plots the predicted closure pressure against the experimental pressure-time history for the above explosion. Differences between the predicted direct pressure, an exponential decay in time, and its experimental counterpart are so slight that the predicted direct pressure is not plotted. At closure, the curves differ in shape; however, the average overpressure magnitudes agree to within 15%. The closure pulses start at slightly different times, but their durations agree to within 15%.

For the structural analysis in the next chapter, we can improve the pressure prediction empirically. A typical pressure-time history is obtained from data and compared to its corresponding empirically determined similitude pressure-time history. The resulting scale factors are applied to the empirical similitude pressures for the explosive configuration of interest and highly accurate pressures are obtained.

2-3 Application of Bulk Cavitation Theory

Of recent interest is the pressure-time history from a 18141 kg (40,000 lb) charge of HBX-1 at 61.0 m (200 ft) depth of burst. Using the analysis in Section 2-1, we obtain the cavitation boundary and closure curves and present them in Figure 6. The pressure-time history corresponding to 305 m (100 ft) horizontal range and 4.88 m (16 ft) depth is shown in Figure 7. Closure is estimated to occur at 4.57 m (15 ft) depth for this range. Judging from the pressure comparison in Figure 5, one expects the predictions for the time at which closure begins and the shape of the closure pulse to contain some error. However, an error in closure time is not likely to affect the damage of a structure subjected to this loading. Also, the calculated closure pulse shape lacks detail, but this may not represent a serious difficulty since in Figure 5 the measured and calculated closure pulses appear to have approximately the same impulse.

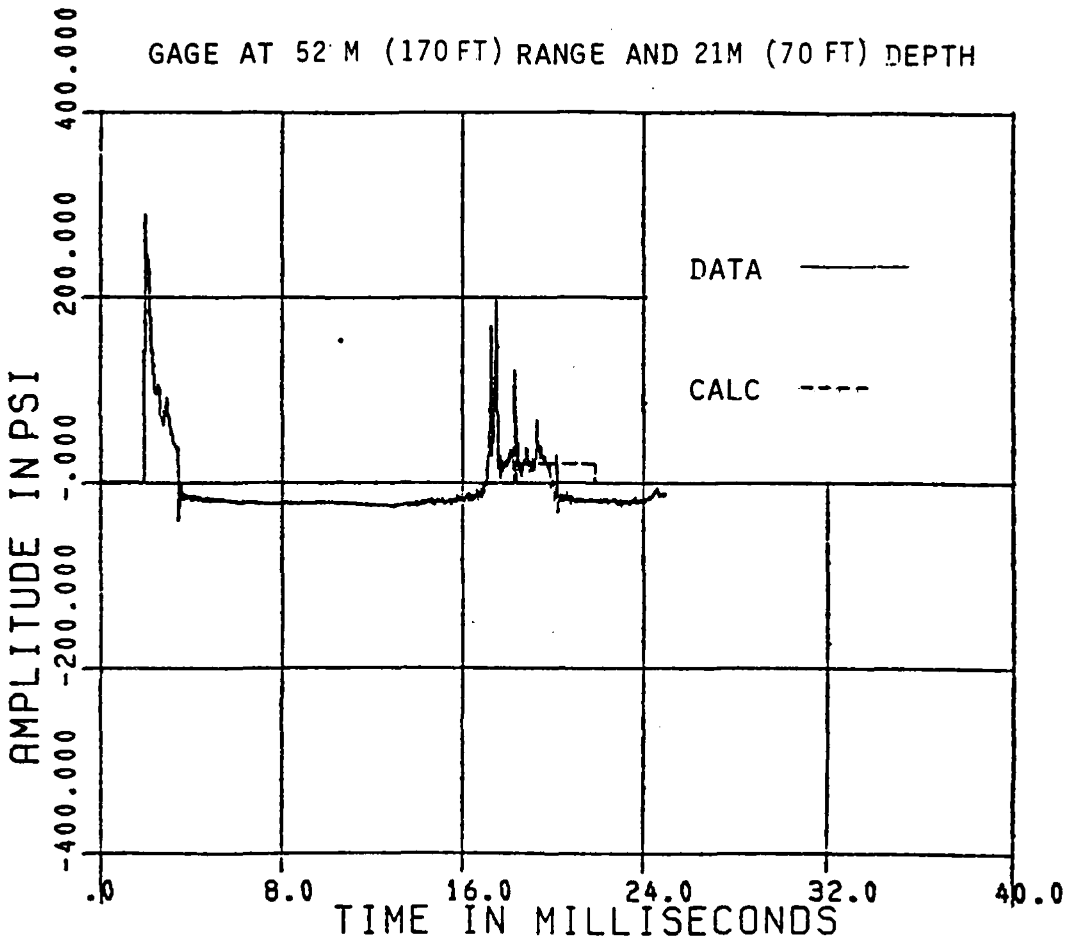

FIGURE 5. CLOSURE PRESSURE COMPARISON FOR 30.8 KG (68 LB) CHARGE OF PENTOLITE

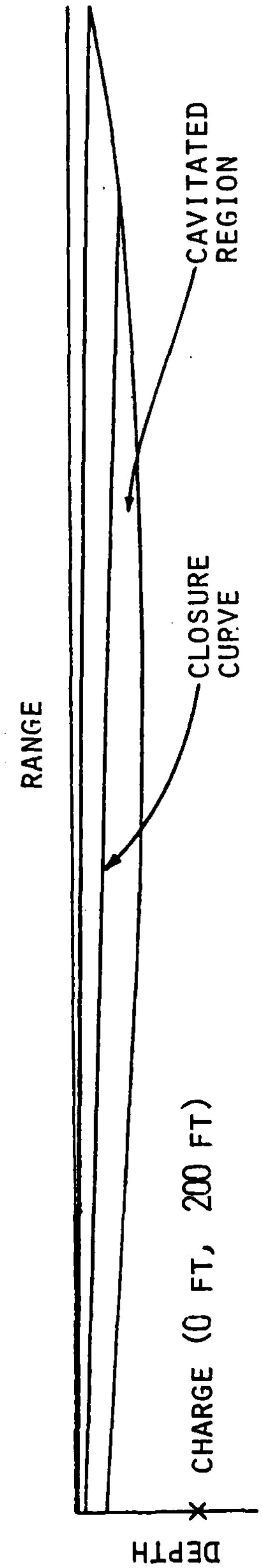

FIGURE 6. BULK CAVITATION FOR 18141 KG (40,000 LB) CHARGE OF HBX–1

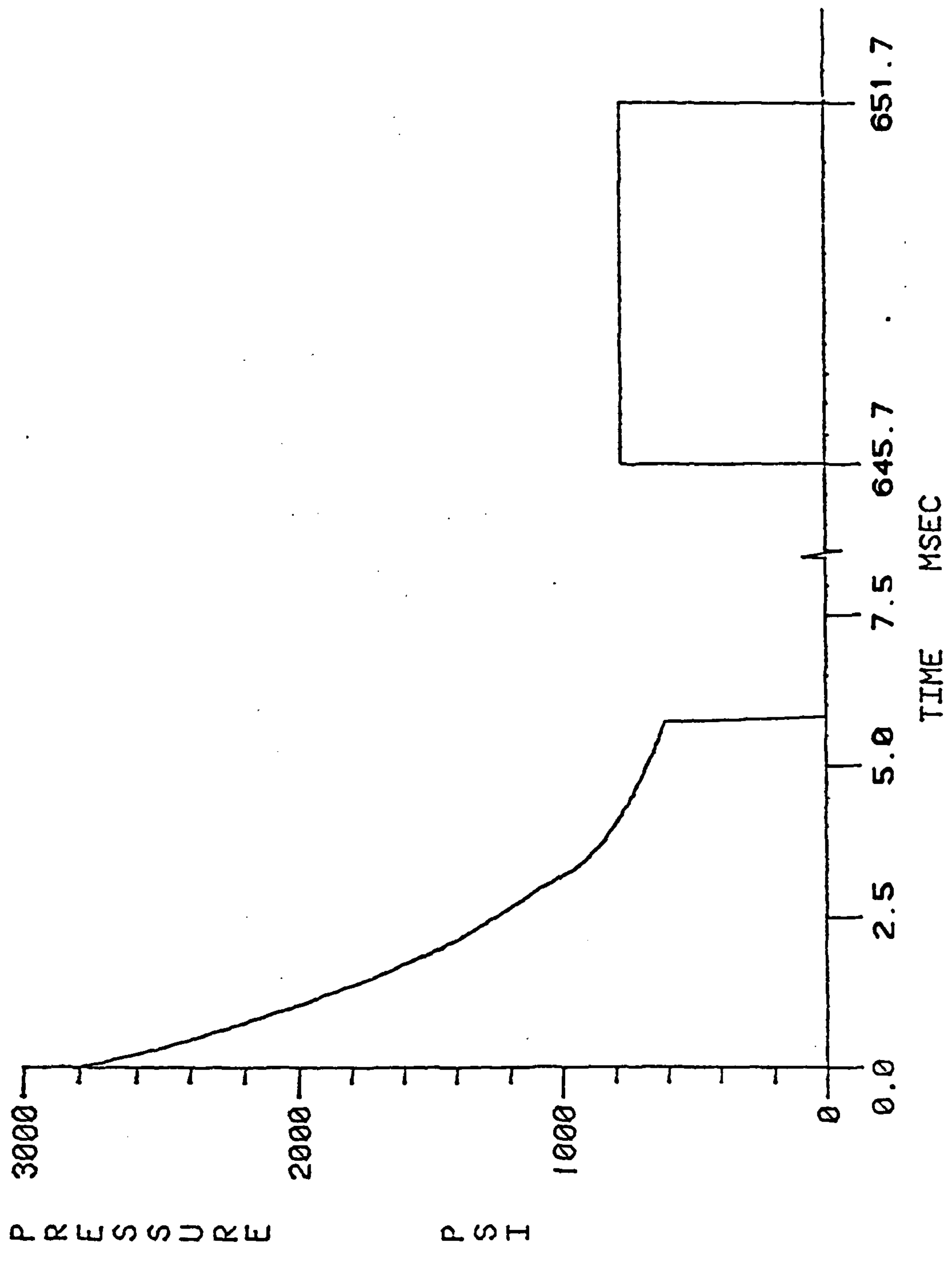

FIGURE 7. CALCULATED PRESSURE–TIME HISTORY FOR 18141 KG (40,000 LB) CHARGE OF HBX–1

CHAPTER 3

PROCEDURE

For underwater structures in dynamic loading, fluid-structure interaction must be taken into account. Of the prominent techniques for the treatment of fluid-structure interaction is the DAA (Doubly Asymptotic Approximation)[14]. Of the structural computer programs implementing the DAA, USA-STAGS has given good results[15].

As discussed earlier, a pressure-time history in a medium undergoing bulk cavitation has three phases:

i) the direct pressure,

ii) zero pressure due to cavitation, and

iii) a positive pressure (assumed constant in this analysis) due to cavitation closure.

The first phase concerns the direct pressure from the explosion described in Section 2-3. Fluid surrounds the cylinder, so USA-STAGS is used to predict the response. In the second phase STAGS, without fluid-structure interaction, predicts the deformation. Finally, USA-STAGS restarts the problem from the end of the second phase and predicts the deformation due to a constant incident pressure.

In the first phase, the calculation must take into account the spherical spreading of the direct pressure wave. There is no pressure in the second phase, but the closure pulse in the third phase effectively does not spread. The point on the closure curve closest to the gage is preceded and followed by points with similar closure times and pressures. Also, the bulk cavitation problem has radial symmetry around the vertical axis of the explosive. Thus the pressure is the same in the angular direction and nearly the same in the radial direction. With nearly symmetric behavior in two almost perpendicular directions, the closure pressure can be called plane.

---

[14]Geers, T. L. "Transient Response Analysis of Submerged Structures," in Finite Elements Analysis of Transient Non-Linear Behavior, AMD Vol. 14, ASME, New York 1975.

[15]Giltrud, M. E., and Lucas, D. S., "A Numerical Comparison with an Exact Solution for the Transient Response of a Cylinder Immersed in a Fluid," Shock and Vibration Bulletin, Sep 1979.

The model target is a 5.08 cm (2 in) length by 12.7 cm (5 in) radius steel cylindrical shell with 8.19 mm (0.323 in) thickness. It is placed at the location mentioned in Section ?-3 and oriented for the direct pressure to hit it at normal incidence. Its structural model has 24 15° elements, making one 360° full model.

For the numerical integration of the structural equations, an implicit method by K. C. Park[16] is used. The time step sizes used in this analysis are shown in Figure 8.

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[16]Park, K. C., "An Improved Stiffly Stable Method for Direct Integration of Non-Linear Structural Dynamics," Jour. App. Mech., Vol. 42, 1975, pp. 464-470.

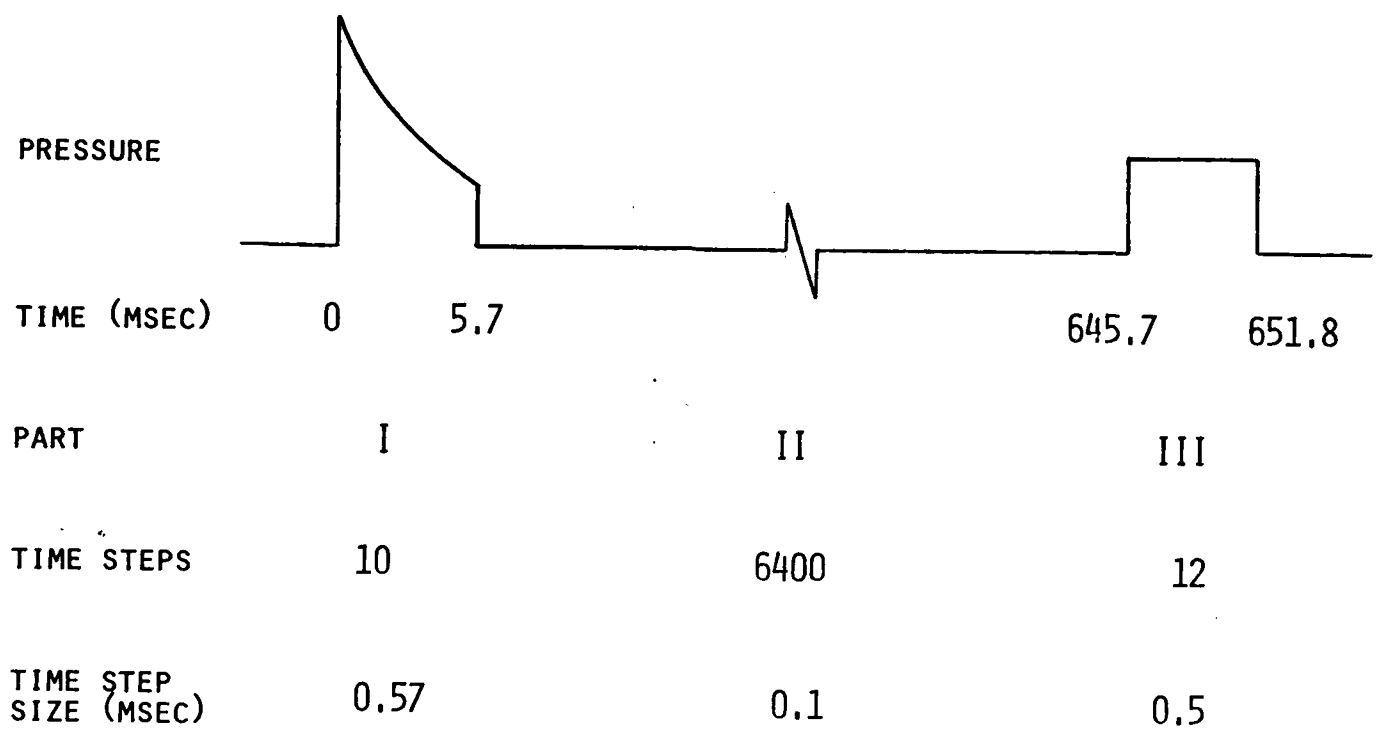

FIGURE 8. TIME STEP SIZES FOR FLUID–STRUCTURE ANALYSIS

CHAPTER 4

RESULTS AND DISCUSSION

The transient analysis required 800 central processor seconds on a CDC Cyber computer. Although results are available in the forms of displacements, velocities, and pressure on the shell, the Von Mises stress criterion indicates yielding and is more appropriate for those interested in structural damage.

Figure 9 shows the Von Mises stress versus time for the part of the structure nearest the explosive charge. The solid curve shows the stress from the direct shock and the dashed curve shows the stress from the cavitation closure. The closure comes 640 msec after the direct shock, but the curves in Figure 9 are presented together for the sake of comparison.

The maximum stress from the direct shock is higher than the maximum stress from closure but for the latter half of the plot, the stresses are nearly the same. If the yield stress of the material were 209 MPa (30 Ksi), then the structure under this load would be dented twice. But it would be dented at two opposite locations, since the closure pulse strikes from above.

In conclusion, bulk cavitation closure may be important in the complete structural response for the model problem, and we have a method to estimate its effect.

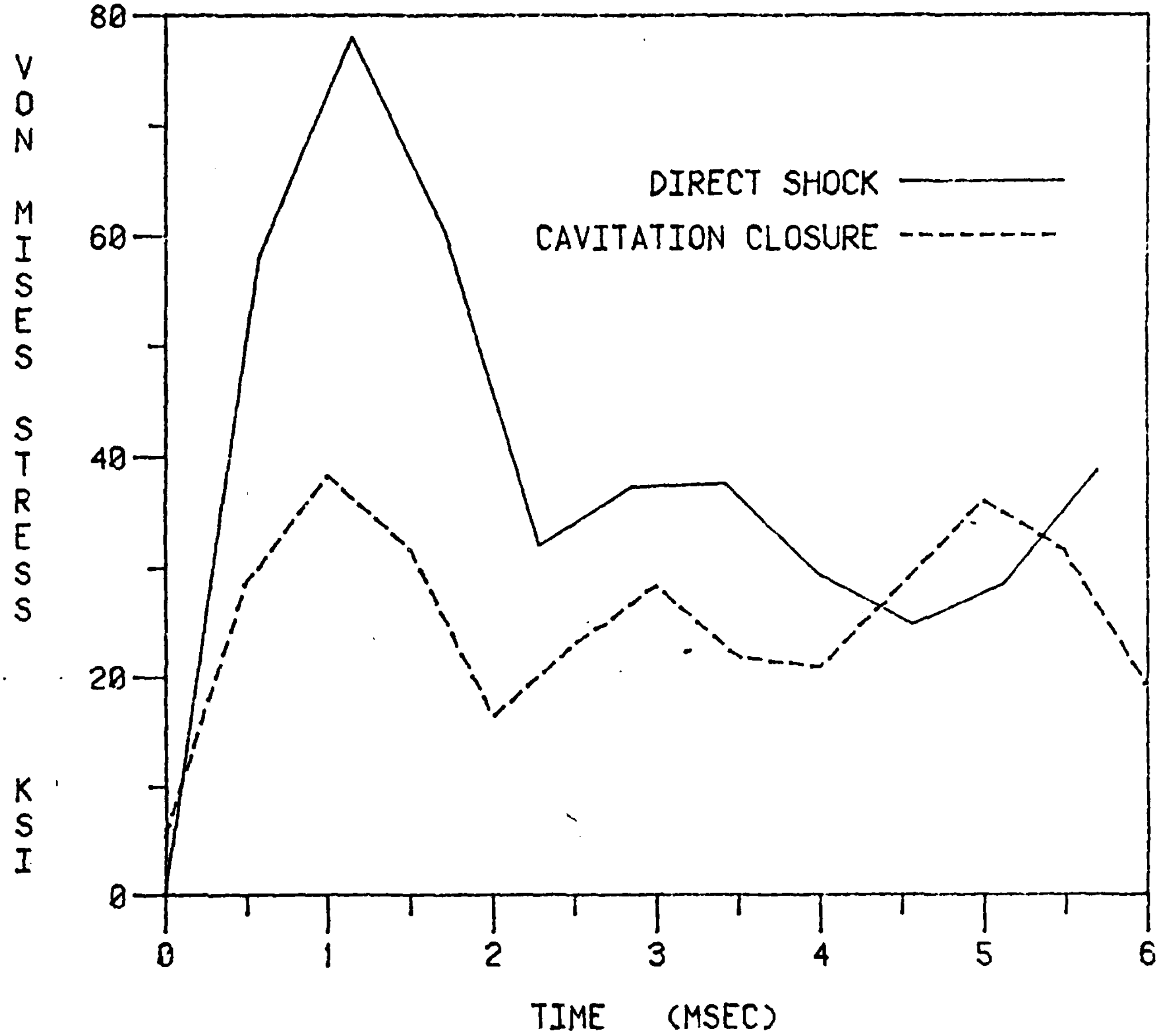

FIGURE 9. STRESS ON CYLINDER AT ELEMENT NEAREST EXPLOSIVE

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